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DESIGN OF IR LASER WINDOWS FOR CRYOGENIC LASERS

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The first part of the report derives expressions for thermal stresses in IR laser windows subjected to uniform cooling. It is shown that the radial contraction effects produce negligible stresses in the window. Fracture of the window is caused by highly localized shear stresses due to axial contraction of the window. A nondimensional plot is given for the determination of the maximum interface shear stress.

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20. Abstract (Continued)

The second part of the report summarizes the results of CaF_2 window cool-down experiments. The results indicate that at least two types of adhesives are suitable for use in cryogenic window assemblies. Based on the above results, CaF_2 laser window assemblies have been designed for use in cryogenic CO electric discharge lasers. These windows have been subjected to thermal cycling between room and LN_2 (77°K) temperatures over the past two years with satisfactory performance.

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SPECIAL TECHNICAL REPORT

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TABLE OF CONTENTS

1.0 INTRODUCTION

The output windows of a cryogenic electric discharge laser must be thermally isolated from the surrounding ambient air to prevent frost formation on the windows. Thermal isolation is achieved by using a double window structure and evacuating the space between the windows. This structure also houses the resonator mirrors of the laser. The window facing the laser cavity provides a smooth boundary to the flowing laser gas and is in thermal equilibrium with the cold gas. The window is also subjected to the pressure of the laser cavity gas. In addition, this window is located between the sustainer high voltage electrodes of the laser. The window seal must be vacuum tight otherwise the low resistance offered by the moderate vacuum path leads catastrophic arcing through the window seal.

If a joint made by joining dissimilar materials is cooled down uniformly and slowly it will still develop internal thermal stresses. These thermal stresses are primarily due to differential shrinkage of the dissimilar materials forming the joint. These stresses are highly concentrated at the corners of a joint and can initiate brittle fracture of the window.

Roberts[1] reports a vacuum tight coolable window seal design for a low temperature optical transmission cell. This design is based upon a thin walled (0.003 in.) annealed copper diaphragm which contains a circular aperture. The window diameter was 1 in. and the use temperature for synthetic CaF_2 windows was 77°K. Rauch and Kernan[2] report on a small diameter liquid helium tight optical window design. A thin walled (0.005 in.) brass tube is used as a holder. The CaF_2 windows used were 0.040 in. thick and 0.5 in. in diameter. The indicated use temperature was 1.1°K. The designs reported in (1) and (2) rely upon metallic holders. Both copper and brass follow the thermal expansion of CaF_2 rather closely. Also these designs were not based on any theoretical foundation. Since the output windows of the laser are in high electrical field, metallic holders cannot be used. From a practical point of view, metals can be used with tighter tolerances and thinner walls. Most dielectric materials, on the other hand, require substantially thicker walls because of their poor machining characteristics. The output windows of the high power lasers usually have a diameter larger than one inch. Since the total contraction of the window is dependent upon the diameter of the window, an analytical way of designing the window holders is necessary.

Consider a circular window joined to a thin walled dielectric tube by means of an adhesive. The cross section of the window holder is shown in Figure 1. The window is subjected to uniform pressure forces and thermal effects due to cool down from room to LN_2 temperatures. The window material will be assumed as an isotropic material and the average mechanical properties will be used in the analysis. Basically, there are three

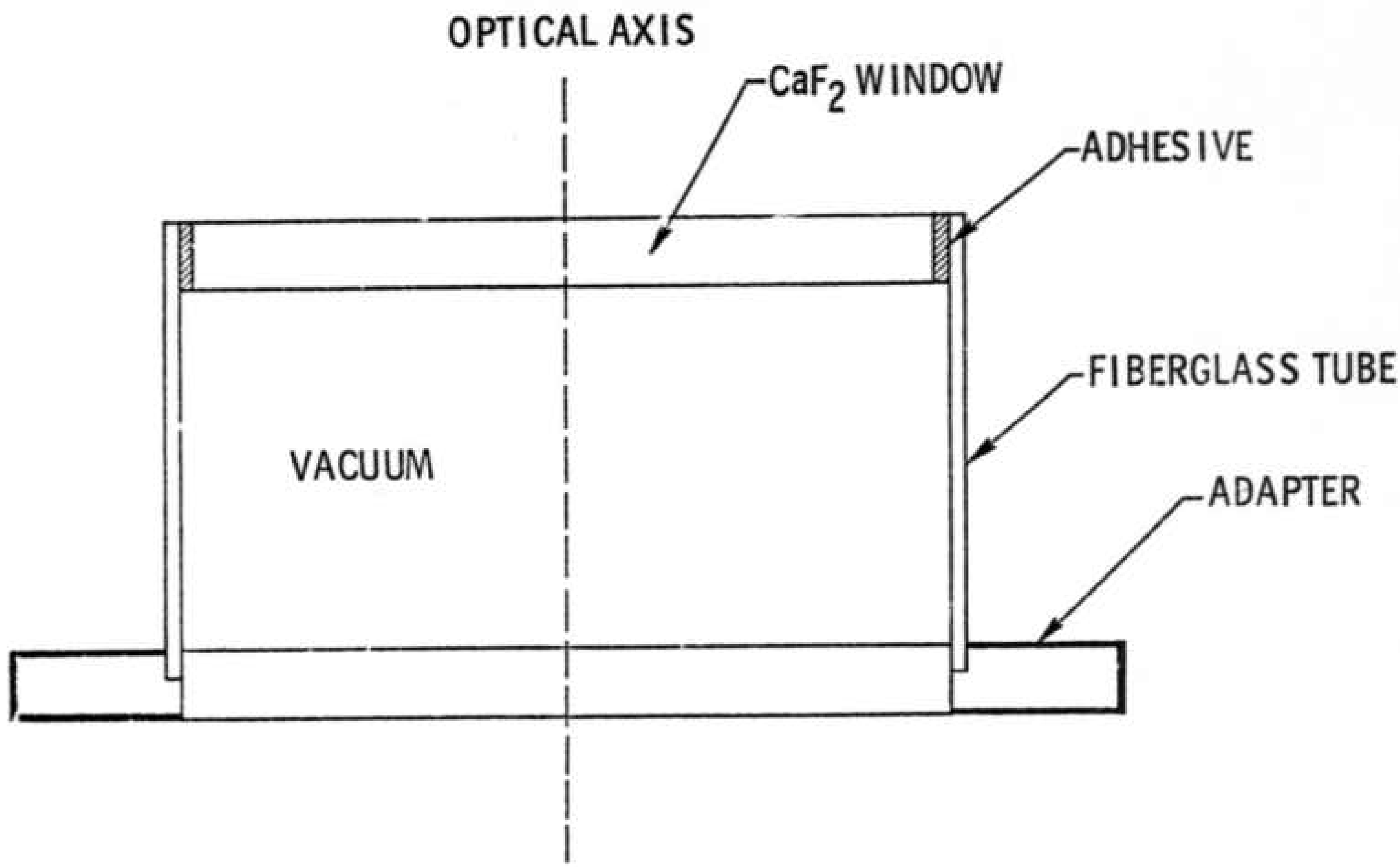


FIGURE 1. CROSS SECTIONAL VIEW OF WINDOW HOLDER

distinct groups of stresses acting on the window:

- (i) Pressure and gross thermal stresses
- (ii) Radial contraction stresses
- (iii) Axial contraction stresses

Pressure and gross thermal effects can be analyzed by modeling the structure as a circular plate mounted on the end of a cylindrical shell. The stresses and distortions are easily obtained using classical shell theories.[3] The window stresses are minimal and the critical stresses occur in the thin walled tube at the junction of the window. In fact, the window thickness is so selected that the distortions and stresses due to pressure are minimal. The classical shell theories, however, omit the localized stresses which occur at the window-tube junction. There are two groups of localized stresses caused by radial and axial contraction of the window. These stresses are schematically shown in Figure 2 for an infinitesimal window element. The radial and circumferential stresses are caused by radial contraction of the window. They depend upon the radial stiffness of the holder tube. The shear stresses and the axial normal stress depend very strongly upon the nature of the joint. These stresses are fairly insensitive to the diameter of the window.

The physical properties of a material depend upon the temperature. As far as thermal stresses are concerned, the most important physical properties are the Young's modulus and the coefficient of thermal expansion. Window and tube materials are relatively stable in the sense that their moduli increases only slightly with decreasing temperature. The adhesives, on the other hand, undergo a recrystallization process at a specific temperature, called the glass transition temperature, which depends upon the constitution of the adhesive. This process is accompanied by abrupt jumps in the Young's modulus of the adhesive.[4, 5] Below the glass transition temperature, adhesives are brittle and their strengths may exceed the strength of the window. In order to determine the stresses accurately the moduli and thermal expansion coefficients must be known as functions of temperature.

This paper is divided into two parts. The first part derives expressions for the thermal stresses developed during a uniform cool-down. The second part summarizes the results of CaF_2 window cool-down experiments.

2.0 THEORY

2.1 Effects of Radial Contraction

Radial contraction effects can be obtained by modeling the window structure as concentric disks (Figure 3). For single disks, the solution to the elasticity equations is given by Timoshenko and Goodier.[6] The solution state for the window can be written as

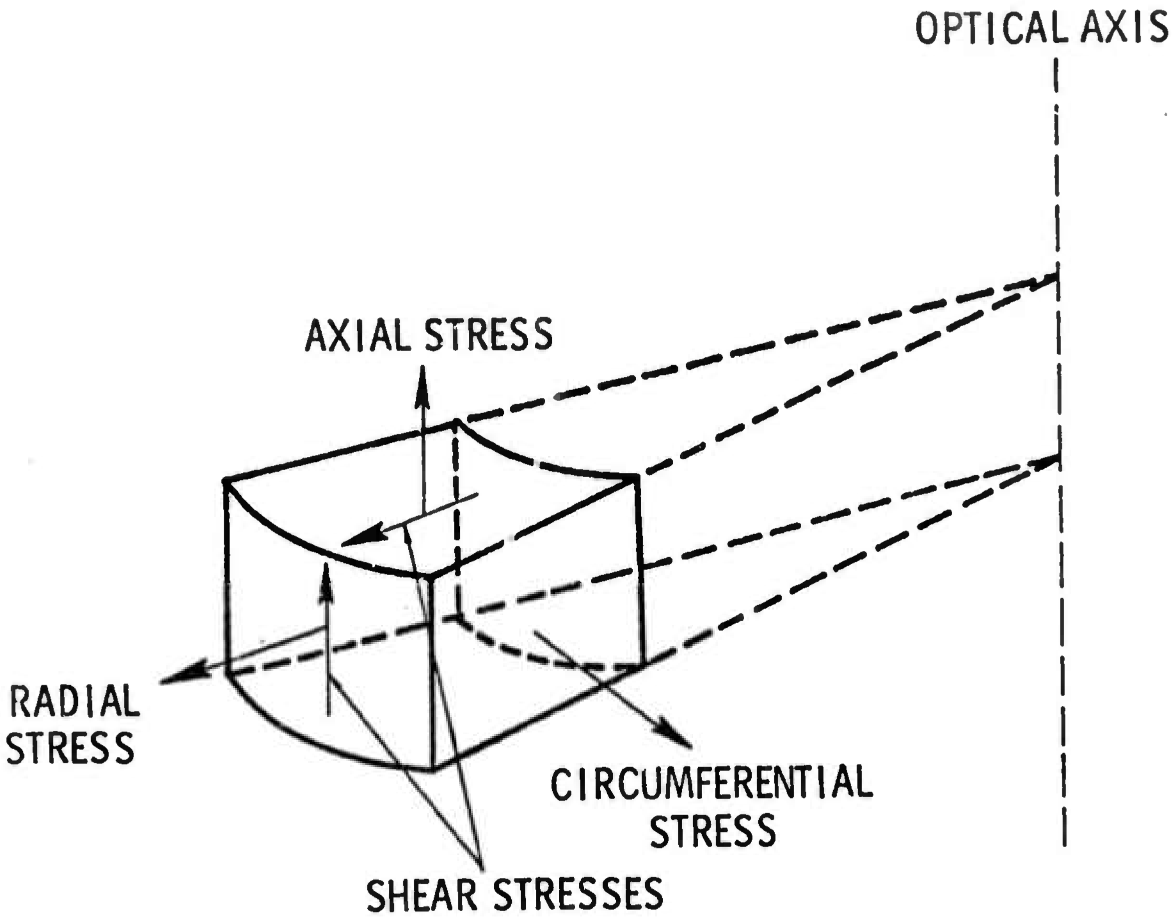


FIGURE 2. STRESSES ACTING ON AN INFINITESIMAL WINDOW ELEMENT.

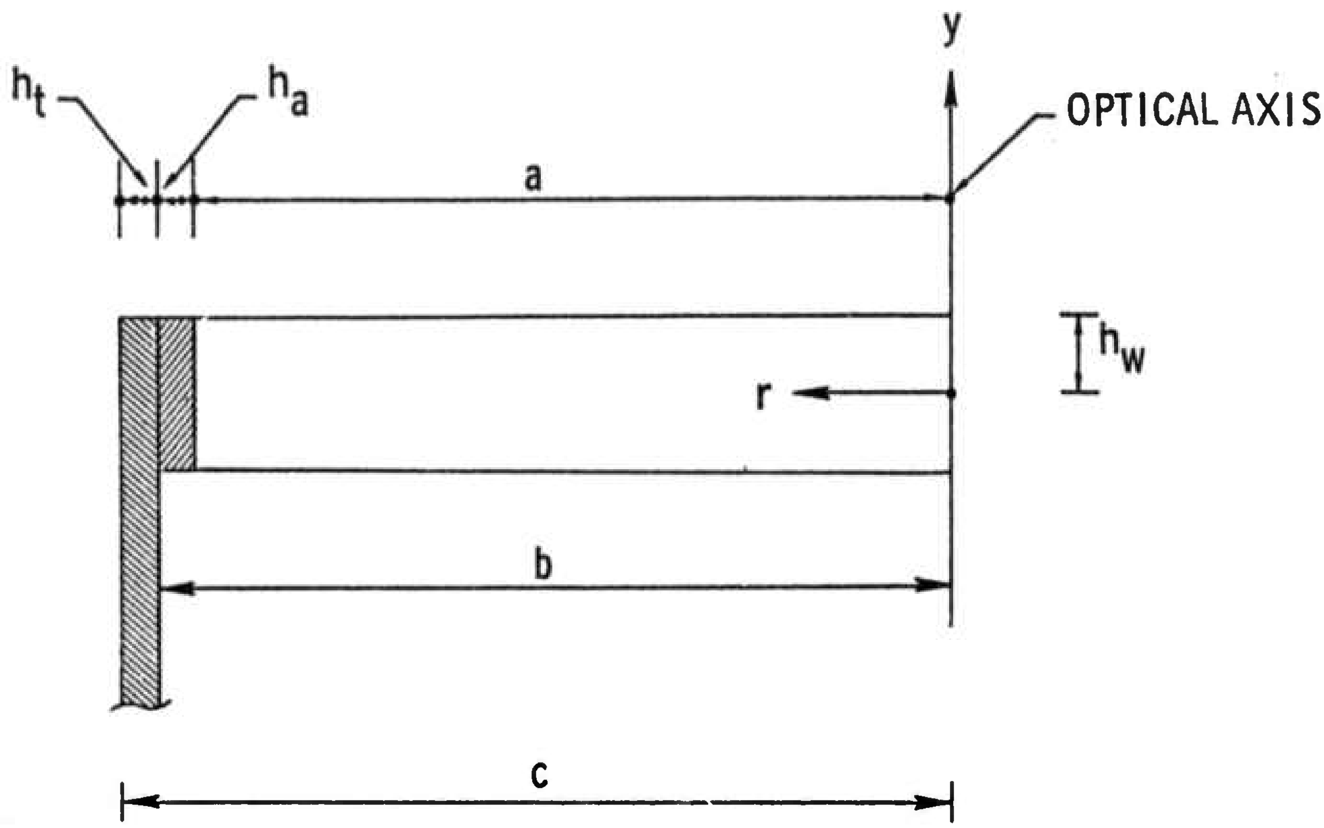


FIGURE 3. CROSS SECTION OF WINDOW-TUBE JOINT.

$$u_w = \frac{1}{2} \alpha_w \Delta T (1 + \nu_w) r + A_w r \tag{1}$$

$$\sigma_{rw} = \sigma_{\theta w} = -\frac{1}{2} E_w \alpha_w \Delta T + E_w A_w/(1 - \nu_w), \tag{2}$$

where u_w is the radial displacement, σ_{rw} and $\sigma_{\theta w}$ are the radial and circumferential stresses, α_w is the coefficient of thermal expansion, E_w is the Young's modulus, ν_w is the Poisson's ratio, and ΔT is the uniform temperature increase. A_w is a constant to be determined from the continuity conditions. The displacement and stresses in the adhesive and tube are given by

$$u = \frac{1}{2} \alpha \Delta T (1 + \nu) (r - r_i^2/r) + Ar + B/r \tag{3}$$

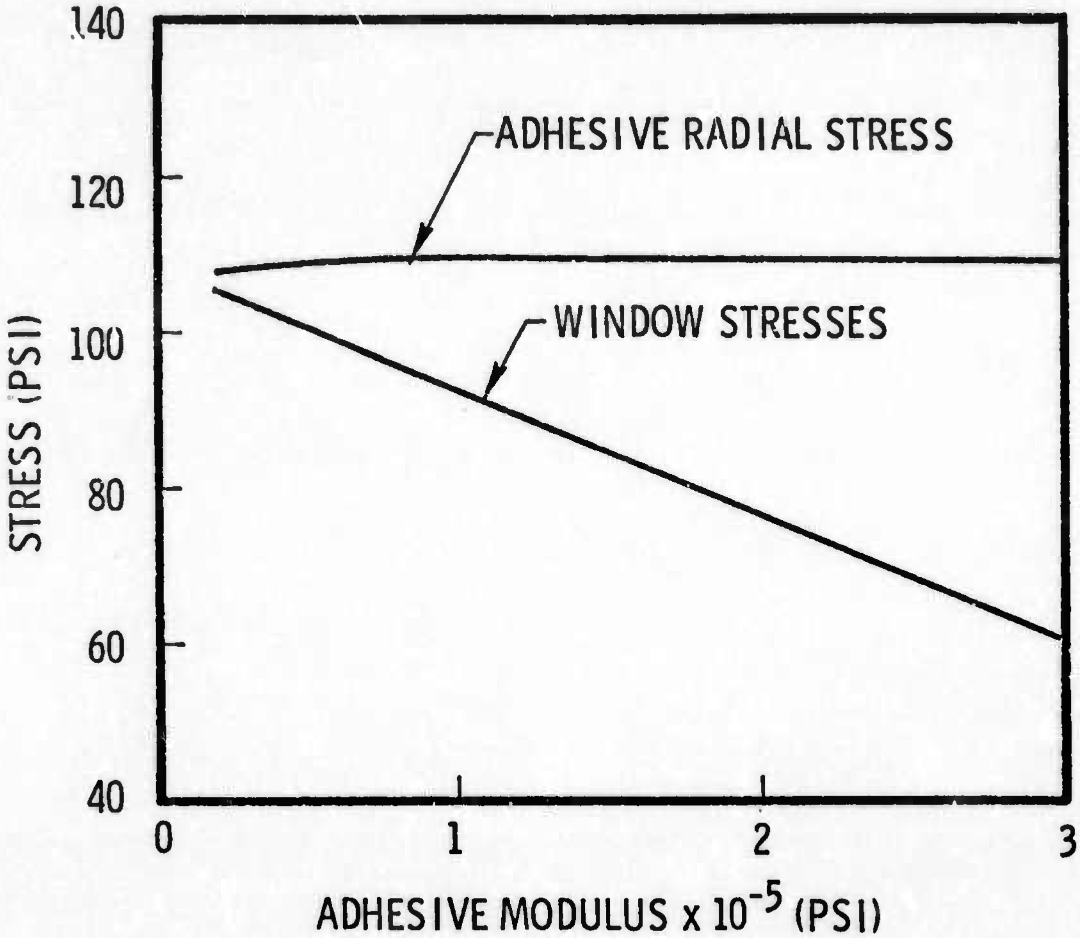
$$\sigma_{\substack{r \\ \theta}} = -\frac{1}{2} E \alpha \Delta T (1 \mp r_i^2/r^2) + E[(1 + \nu) A \mp (1 - \nu) B/r^2]/(1 - \nu^2), \tag{4}$$

where the minus signs in equation (4) refer to radial stress while the plus signs are for the circumferentail stress. Same definitions apply here as well. Since the adhesive and the tube are annular rings their solution state is expressed with two unknown constants, A and B. The radius r_1 is the inner radius of the disk. When differentiation is needed between the adhesive and the tube solutions, we shall use the subscripts a for the adhesive and t for the tube, respectively. The five constants entering into the solution state are found from the interface continuity and the boundary conditions. These conditions are:

at $r = a$	$u_w = u_a$	(5a)
	$\sigma_{rw} = \sigma_{ra}$	(5b)
at $r = b$	$u_a = u_t$	(5c)
	$\sigma_{ra} = \sigma_{rt}$	(5d)
at $r = c$	$\sigma_{rt} = 0$	(5e)

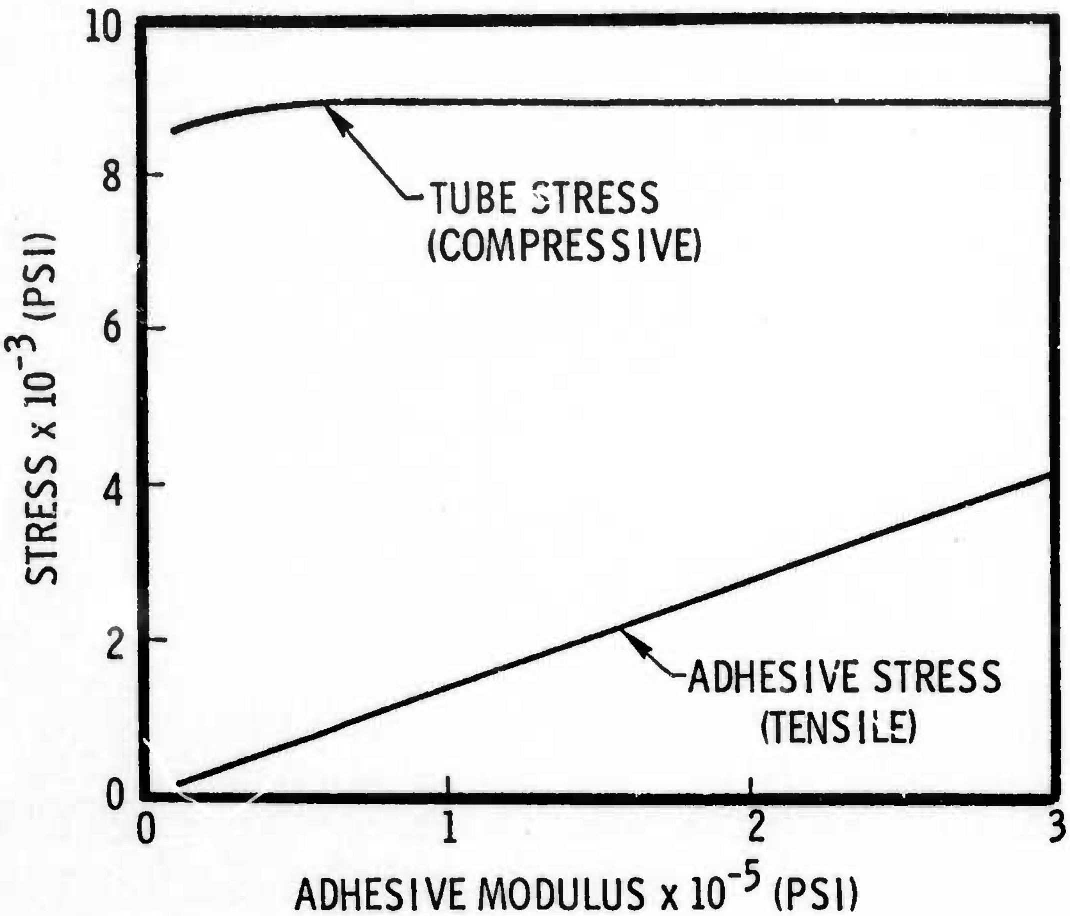
After the unknown constants are obtained from equations (5) the complete solution state is given by the equations (1) - (4).

In the above treatment the physical properties are assumed to be independent of temperature. This is done because there is not enough data representing the variation of the moduli with temperature. To assess the importance of the variable properties, the stresses developed for uniform cool-down from room to LN_2 temperatures are plotted in Figures 4 and 5 for various values of adhesive modulus. The window material is CaF_2. It is seen that the window stresses are very small. This is so because in the



WINDOW DIAMETER = 4 IN., ADHESIVE THICKNESS = 0.025 IN., TUBE WALL THICKNESS = 0.025 IN., UNIFORM TEMPERATURE DECREASE = 400^{0}F, TUBE MATERIAL = FIBERGLASS

FIGURE 4. RADIAL STRESSES CAUSED BY UNIFORM COOL-DOWN.



WINDOW DIAMETER = 4 in., ADHESIVE THICKNESS = 0.025 IN., TUBE WALL THICKNESS = 0.025 IN., UNIFORM TEMPERATURE DECREASE = 400°F, TUBE MATERIAL = FIBERGLASS

FIGURE 5. CIRCUMFERENTIAL STRESSES CAUSED BY UNIFORM COOL-DOWN.

radial direction the window is much stronger than the thin walled tube. As far as the window stresses are concerned, the radial contraction effects are negligible. Thus, the design can be scaled to even larger diameter windows. Same conclusions cannot be drawn for tube and adhesive materials, however. The larger the window diameter, the higher the tube and adhesive stresses are. Note also that the tube stresses are not strongly influenced by the choice of the adhesives.

2.2 Effects of Axial Contraction

The stresses caused by the axial contraction of the window are concentrated near the adhesive joint. An integral boundary layer approach will be used in the following derivation. We shall also assume that the window thickness is much smaller than its radius, the adhesive and tube wall thicknesses are smaller than the window thickness, and that the axial stresses in the adhesive can be neglected. The last assumption is justifiable since the adhesive modulus is much smaller than that of the window.

Referring to Figure 6, the equilibrium equations for the window and the tube can be written as

$$dN_w/dy + 2\pi a \tau = 0 \tag{6}$$

$$dN_t/dy - 2\pi a \tau = 0 \tag{7}$$

where N_w is the integrated window axial stress, τ is the interface shear stress, and N_t is the axial tube force. The constitutive equations relating the stresses to the strains are given by

$$\sigma_w = E_w\,(\partial u_w/\partial y - \alpha_w\,\Delta T) \tag{8}$$

$$\tau = G_a \gamma_a \tag{9}$$

$$\sigma_t = E_t\,(\partial u_t/\partial y - \alpha_t\,\Delta T) \tag{10}$$

where G_a is the adhesive shear modulus, γ_a is the adhesive shear strain, and the window and the tube displacements (parallel to optical axis) are denoted by u_w and u_t. Using the boundary layer approximation,[7] we can express the displacements by

$$u_w(r, y) \sim V_w(y)\, I_0(\gamma r)/I_0(\gamma a) + y\alpha_w\,\Delta T \tag{11}$$

$$u_t(r, y) \sim V_t(y) \tag{12}$$

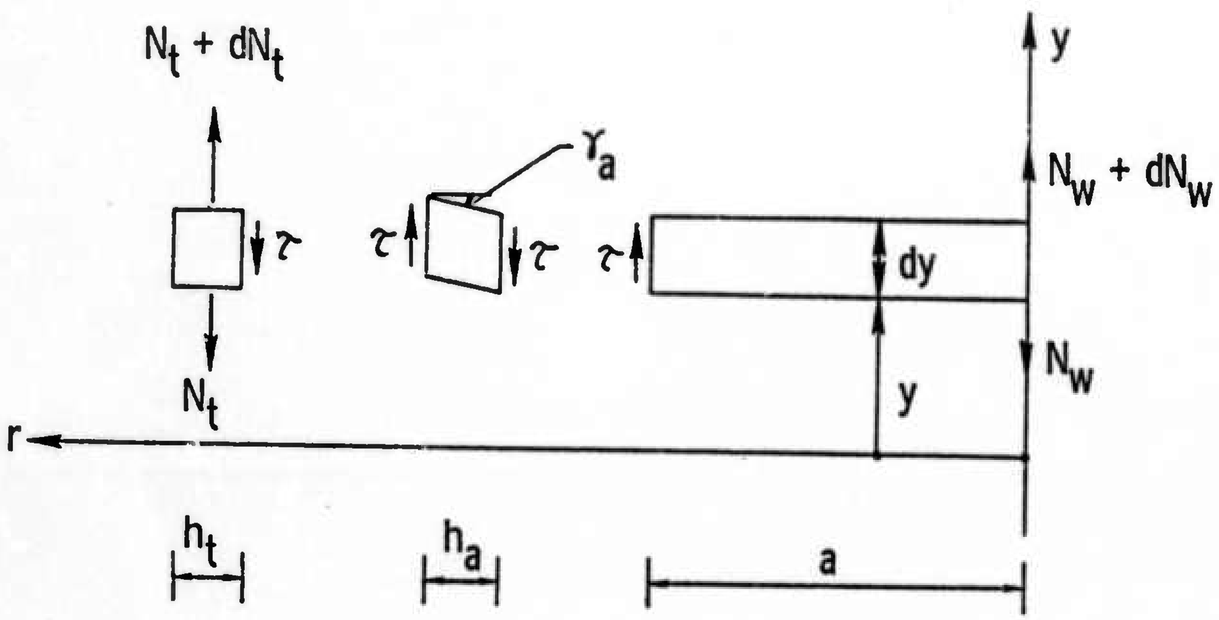


FIGURE 6. THE INTERNAL FORCES ACTING ON WINDOW, ADHESIVE, AND TUBE ELEMENTS.

where

$$\gamma^2 = 12\, E_w / h_w^2\, G_w \tag{13}$$

is the boundary layer stretching parameter and I_0 refers to modified Bessel function of order zero. From the geometry of the joint, the adhesive shear strain can be found as

$$\gamma_a = (V_t - V_w - y\, \alpha_w \Delta T)/h_a . \tag{14}$$

The axial forces entering into the equilibrium equations (6) and (7) are found by integrating the constitutive equations (18) and (10):

$$N_w = 2\pi \int_0^a \sigma_w\, r dr = (2\pi a\, I_1(\gamma a)/\gamma\, I_0(\gamma a))\, E_w\, dV_w/dy \tag{15}$$

$$N_t = 2\pi a\, h_t\, \sigma_t = 2\pi a\, h_t\, E_t\, (dV_t/dy - \alpha_t\, \Delta T). \tag{16}$$

The equations of equilibrium (6) and (7) can now be expressed in terms of two unknown displacements (V_w and V_t) using (9), (14), (15), and (16). These two differential equations must be solved in conjunction with the following boundary conditions:

at	$y = 0$	$V_t = V_w = 0$	(symmetry)	(17a)
at	$y = \frac{1}{2} h_w$	$N_t = N_w = 0$	(free edge).	(17b)

The interface shear stress is the quantity of interest. Omitting the details, the interface shear stress is obtained as

$$\tau = \frac{1}{2} (G_a\, h_w\, (\alpha_t - \alpha_w)\, \Delta T/h_a)\, (\sinh\, (2\beta y/h_w)/\, \beta \cosh \beta) \tag{18}$$

where β is the normalized stiffness parameter and is given by:

$$\beta = \frac{1}{2} h_w \left\{ \gamma G_a\, I_0(\gamma a)/h_a\, E_w\, I_1\, (\gamma a) + G_a/h_a\, h_t\, E_t \right\}^{\frac{1}{2}} \tag{19}$$

The maximum shear stress occurs at the edge of the window where $y = h_w/2$. If the properties are independent of temperature, the maximum shear stress can be expressed in terms of a normalized shear stress which is a function of normalized stiffness parameter alone, i.e.,

$$\tau^* = \tau_{max} / \left(\frac{1}{2} G_a (\alpha_t - \alpha_w) \Delta T\, h_w/h_a\right) = \tanh\beta/\beta \tag{20}$$

The variation of the normalized shear stress as a function of the normalized stiffness parameter is given in Figure 7. If the physical properties are functions of temperature then the shear stress distribution is given by the following equation

$$\tau = \frac{1}{2} h_w/h_a \int_0^{\Delta T} G_a(\alpha_t - \alpha_w) \sinh(2\beta y/h_w)/\beta\cosh\beta \; dT. \tag{21}$$

The maximum shear stress obtained either from Figure 7 or from equation (21) must be less than the shear strength of the window material for a successful design.

3.0 EXPERIMENTAL RESULTS

The selection of the right adhesive to bond the CaF_2 window to the thin walled tube is very important. This is because at cryogenic temperatures the adhesives are strong enough to initiate brittle fracture of CaF_2. The proper adhesives were found as a result of simple experiments. In these experiments, the central region of a CaF_2 piece wa uniformly coated with adhesive. The thickness of the adhesive was selecte as 0.020 in. The adhesive was cured following the manufacturer's recommendations. Later, the adhesive-CaF_2 combination was slowly cooled to LN_2 temperature. The bond surface was then examined to see whether or not there was interface cracking in the window or peeling off of the adhesive. Several adhesives either peeled off from CaF_2 or caused fracture of the CaF_2 piece. The acceptable adhesive-CaF_2 joints were thermally cycled to observe the result of alternating thermal loading. The resulting acceptable adhesives are listed in Table 1.

The interface shear stress distribution is strongly influenced by the voids in the adhesive. These voids act as stress raisers and may initiate the fracture of the window as well as cause the adhesive to separate from the window. To eliminate these voids, a special fixture has been built for bonding the CaF_2 windows to thin walled tubing. Figure 8 shows this fixture together with a 4 in. diameter CaF_2 window bonded to a short, thin walled fiberglass tube. The window mounting technique is greatly simplified by this fixture. The lower circular plate holds a cylindrical Teflon block which supports the CaF_2 window. The upper ring supports the thin walled fiberglass tubing. After mounting the window and the tube, the fixture is heated to 150°F. Immediately after heating, the side of the window is coated with the warm adhesive. Next, the ring supporting the fiberglass tubing is raised slowly, which causes the tube to slide over the adhesive coated window. With the aid of this fixture we have consistently produced void-free adhesive joints.

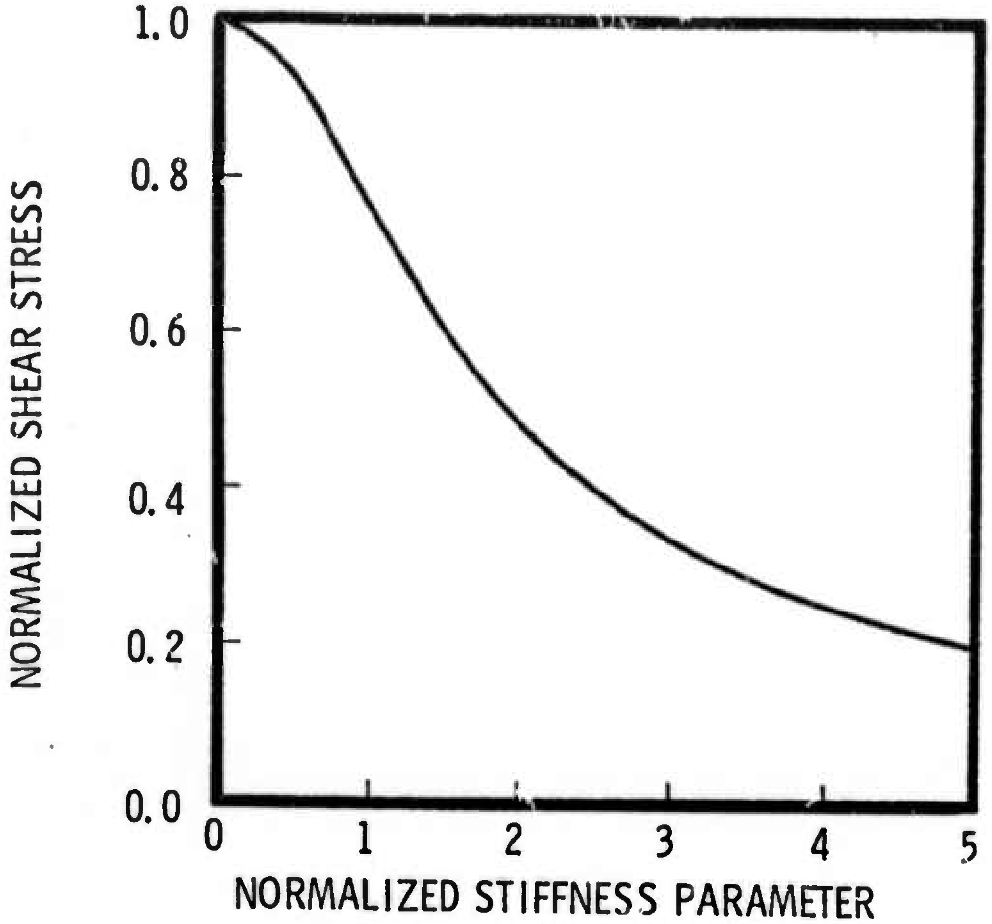


FIGURE 7. NORMALIZED MAXIMUM WINDOW EDGE SHEAR STRESS AS FUNCTION OF STIFFNESS PARAMETER.

Table 1. Acceptable Adhesives for CaF_2 Bonds. Figures in Parenthesis Indicate Weight Ratios.

Epon 828 + Versamid 125	(30/70)
Genepoxy M180 + Versamid 125	(35/65)
Bakelite Epoxy 2774 + Versamid 140	(11/14)
Epon 828 + Epon 871 + NMA + BDMA	(30/70/90/3)
Polyurethane	-

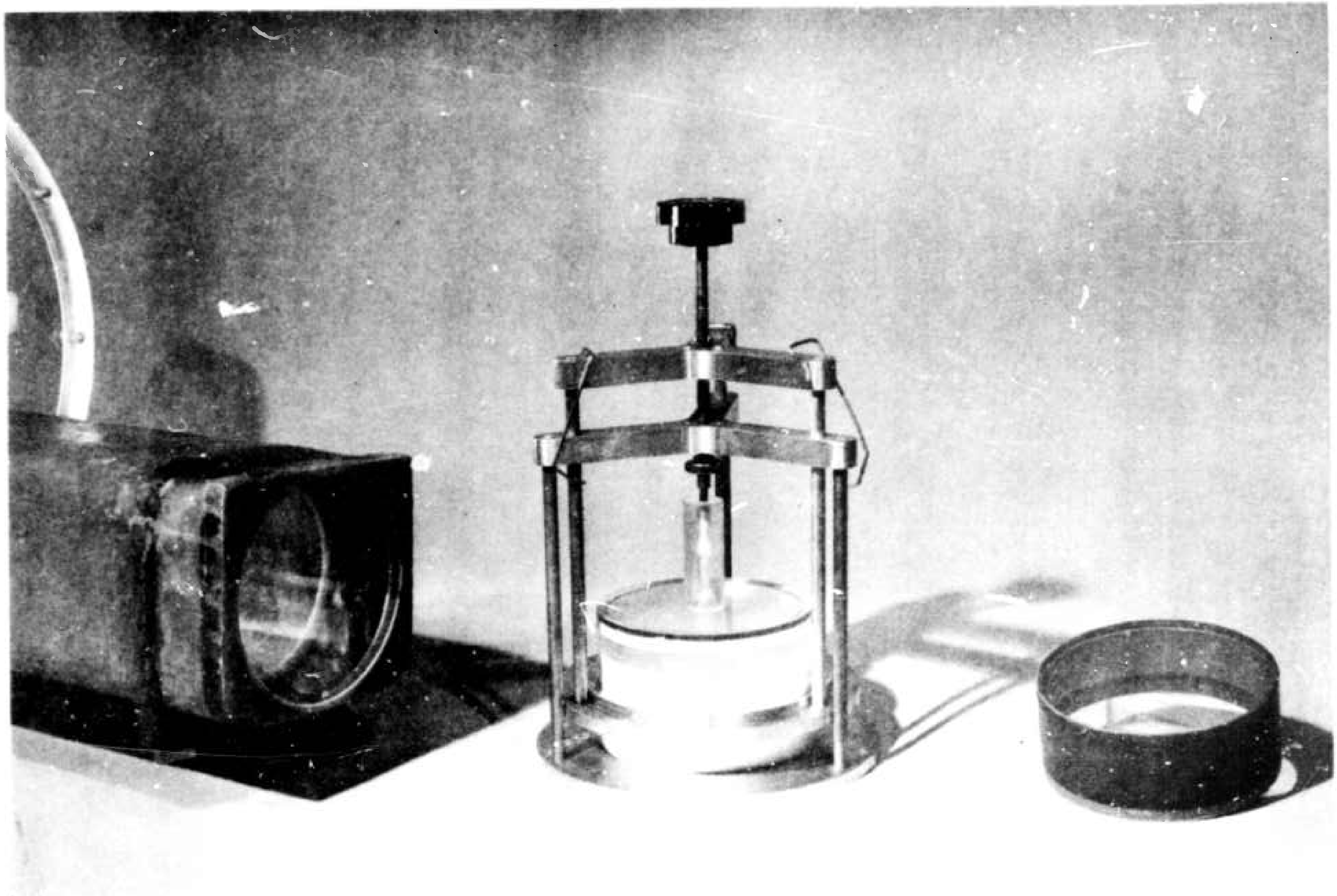


FIGURE 8. SPECIAL FIXTURE TO BOND CaF_2 WINDOWS TO THIN WALLED FIBERGLASS TUBES.

4.0 CONCLUSIONS

Based on the results described above, CaF_2 window assemblies were designed and constructed for use in cryogenic lasers. During the last two years, these CaF_2 window assemblies were used in Northrop's cryogenic CO electric discharge lasers. These windows were subjected to repeated thermal cycling between room and LN_2 (77°K) temperatures with satisfactory performance.

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